TESTS TO EVALUATE THE EFFECT OF A WATERJET BARRIER ON THE BURNING EFFICIENCY OF A FLOATING OIL SLICK

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TESTS TO EVALUATE THE EFFECT OF A WATERJET BARRIER ON THE BURNING EFFICIENCY OF A FLOATING OIL SLICK

by

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1.0 INTRODUCTION ET OBJECTIFS DU PROJET

Au cours de la dernière décennie, on s'est efforcé de mettre au point des méthodes efficaces d'intervention contre les nappes d'hydrocarbures.

L'emploi de jets d'eau a été étudié pour rassembler et localiser les nappes. Les jets à faible pression ont été éprouvés comme barrières incombustibles (Comfort, 1980). Par la suite, un dispositif de projection à forte pression a été imaginé, et un gros prototype construit (Meikle et coll., 1985; Meikle, 1983), essayé sur le terrain (p. ex. Laperrière, 1985) et éprouvé en laboratoire. Dernièrement, on a tenté d'en optimiser la configuration (p. ex. pression de fonctionnement, angle d'incidence, écartement des buses de projection) pour la localisation des nappes (Phillips et coll., 1987).

Toutefois, l'effet des jets sur l'efficacité du brûlage des hydrocarbures n'a pas été vérifié. On pensait que la barrière à jets d'eau améliorerait le brûlage grâce à une meilleure aération de la flamme. Notre travail visait à clarifier la question.

Les objectifs précis du programme d'essais étaient d'évaluer:

a) l'effet de la barrière à jets sur l'efficacité volumique et massique du brûlage;

b) l'effet de la barrière sur l'opacité des fumées dégagées durant le brûlage.

1.0 INTRODUCTION AND PROJECT OBJECTIVES

Over the past decade, considerable efforts have been expended towards the development of countermeasures that are effective for floating oil slicks.

Waterjets are one method that has been studied to herd and contain the spilled oil. Low pressure waterjets were tested as fireproof oil slick containment devices (Comfort, 1980). Subsequently, a system of high pressure waterjets was developed for oil spill control and a large prototype system was produced (Meikle et al, 1985; Meikle, 1983). This system has been deployed in the field (eg. Laperriere, 1985) and tested in the laboratory. Recently, tests have been done to optimize the mechanical configuration of the high pressure waterjets (eg. operating pressure, angle of incidence, nozzle spacing) for oil spill retention (Phillips et al, 1987).

However, the effect of the waterjet barrier on oil burning efficiency has not been tested. It was hypothesized that the waterjet barrier may also improve the combustion of the oil by providing greater aeration of the flame. This project has been conducted to improve present understanding of this issue.

The specific objectives of the test program were to:

(a) evaluate the effect of the waterjet barrier on the volumetric and mass oil burn efficiency.

(b) evaluate the effect of the waterjet barrier on the opacity of the smoke plume produced during the burn.

2.0 PROJECT SCOPE

2.1 Test Setup and Description

2.1.1 Test Facilities

Burning tests were conducted in an outdoor basin near Fleet Technology Limited's laboratories in Kanata, Ontario. This basin was 12m x 15m in area and 0.5m deep. See Figures 2.1 and 2.2 and Plate 2.1.

A high pressure waterjet system was supplied by Environment Canada for the tests and was operated by a technician from Sanivan Inc. during the project (See Plate 2.2). The waterjet barrier was deployed in a "V" and a circle configuration, as shown in Figures 2.1 and 2.2 and Plates 2.3 and 2.4. The waterjet barrier is described further in section 2.1.3.

2.1.2 Test Documentation

Each test was documented using colour video photography and 35mm still photographs. Both black and white, and colour photographs were taken.

The following parameters were measured for each test:

(a) Environment Data:
- Air temperature
- Water temperature
- Ambient windspeed and direction

(b) Oil Burn Data:
- Pre-burn weight and volume of the oil
- Weight and volume of the residue
- Density and reflectance of the smoke plume
- Duration of burn
- Flame temperature

Table 2.1 summarizes the techniques used to measure the above parameters.

The oil used for each test was placed in standard 200 litre (45 gal.) drums to determine the pre-burn weight and volume. For the first test, the weight of the oil was measured using a large balance beam scale and the volume was measured using a linear scale. See Figure 2.3 for schematic. These measurements were used to determine the pre-burn weight and volume of the oil for subsequent tests.

At the end of each test, the residue was collected using a combination of pails and shovels. With this collection approach, some water was picked up with the oil. The residue was placed in an oil drum and the water was drained through an outlet at the base of the drum. See Figure 2.3 for schematic.

After the water had been drained, the volume of the residue was measured using a linear scale and the weight was measured using a large balance beam scale.

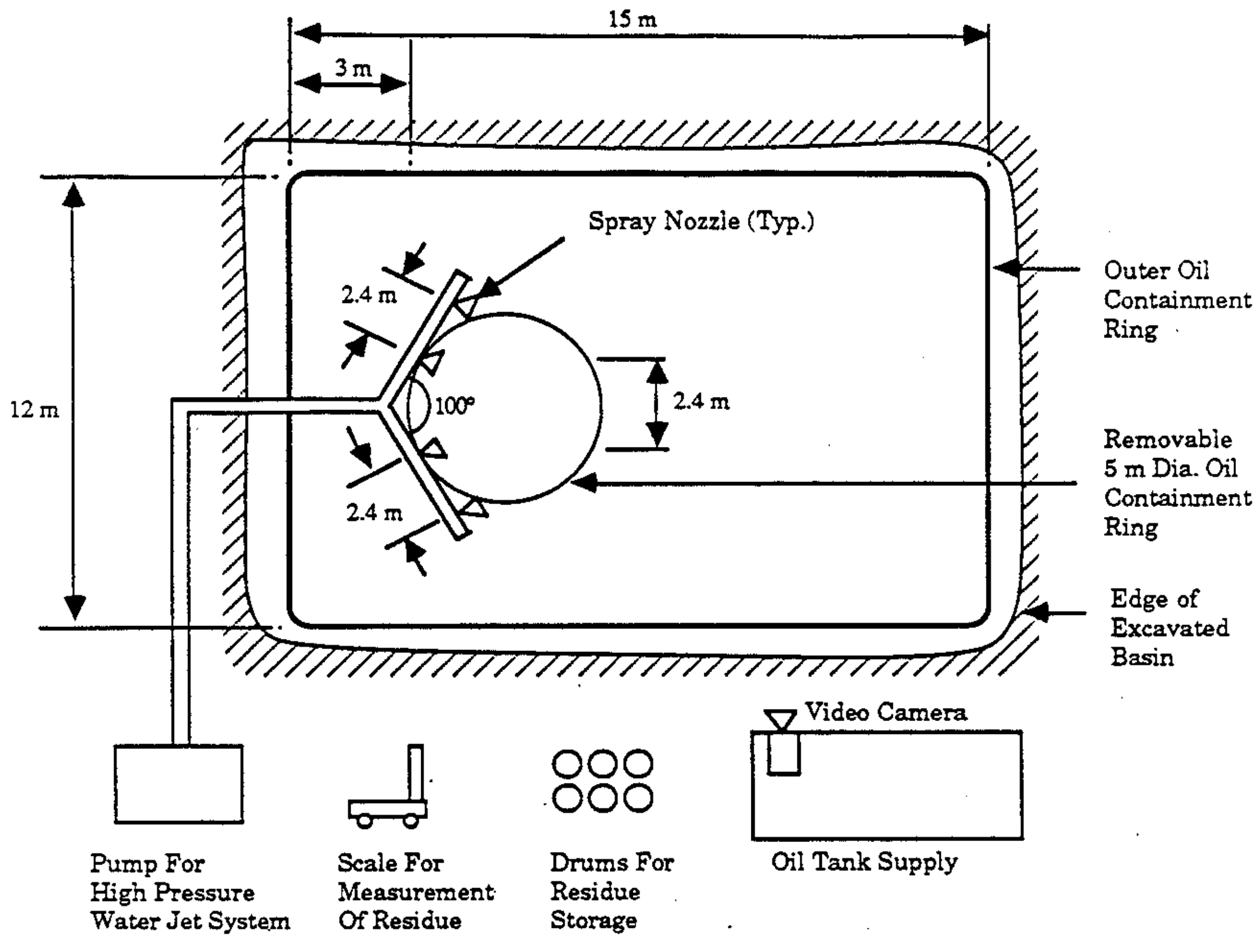


Figure 2.1a Schematic of Test Setup - Waterjet Barrier Configuration "V"

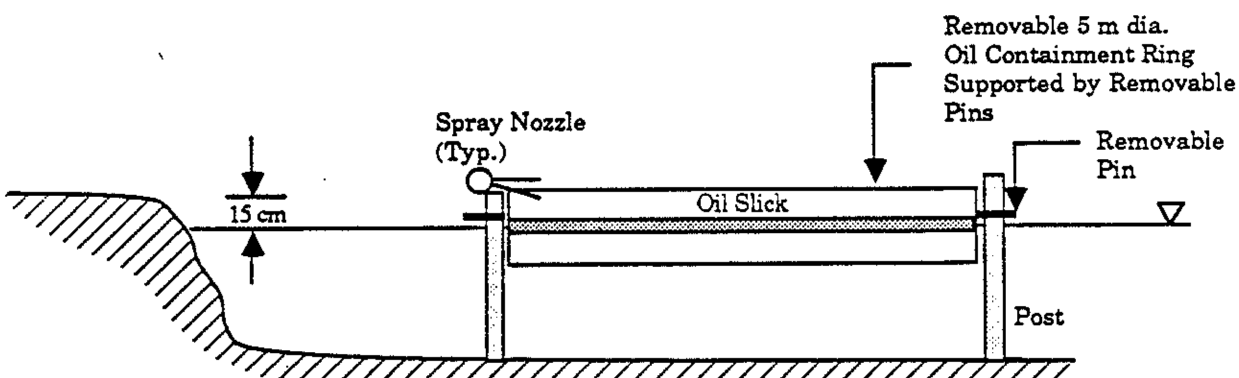


Figure 2.1 b Cross-sectional View: "V" Configuration

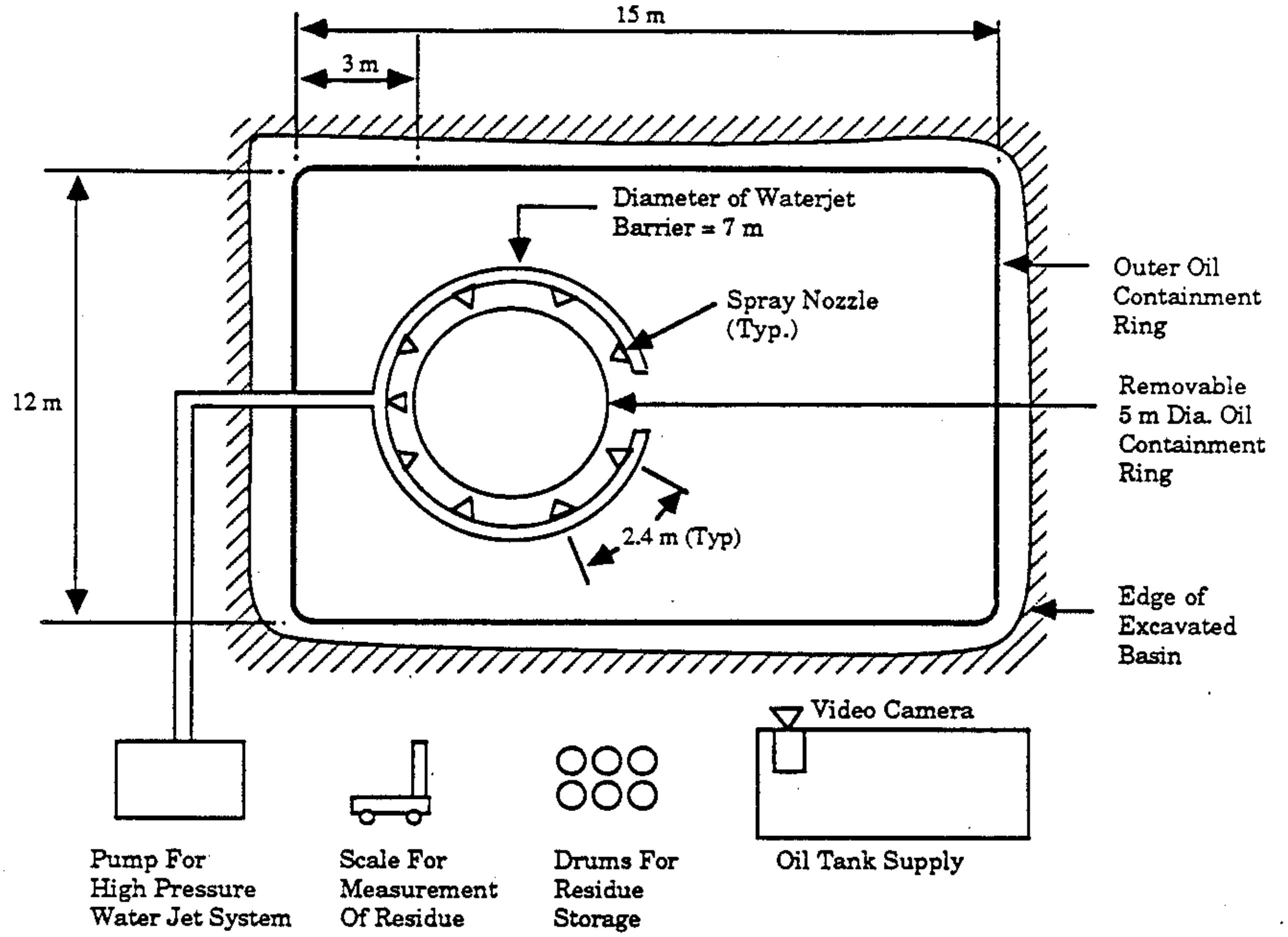
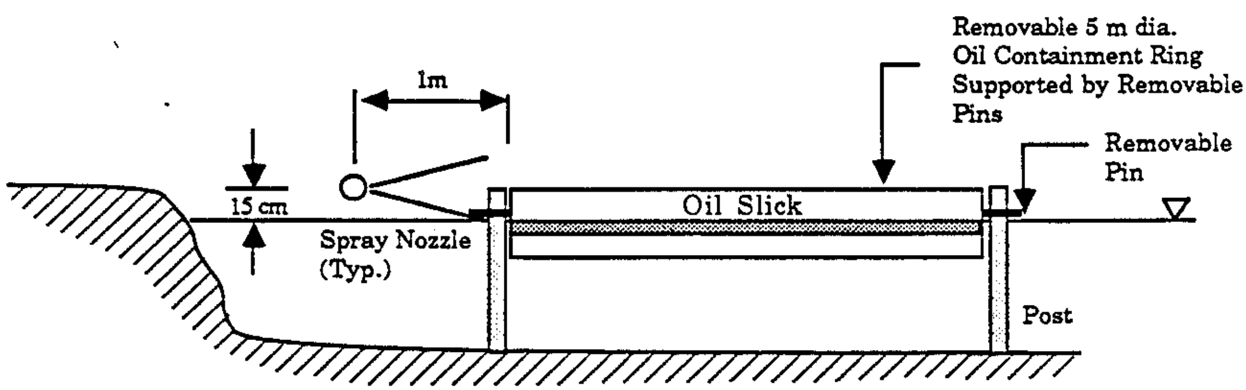


Figure 2.2a Schematic of Test Setup - Waterjet Barrier Configuration: Circle



Note: Centreline of waterjet kept at same elevation as top of containment ring.

Figure 2.2 b Cross-sectional View: Circle Configuration

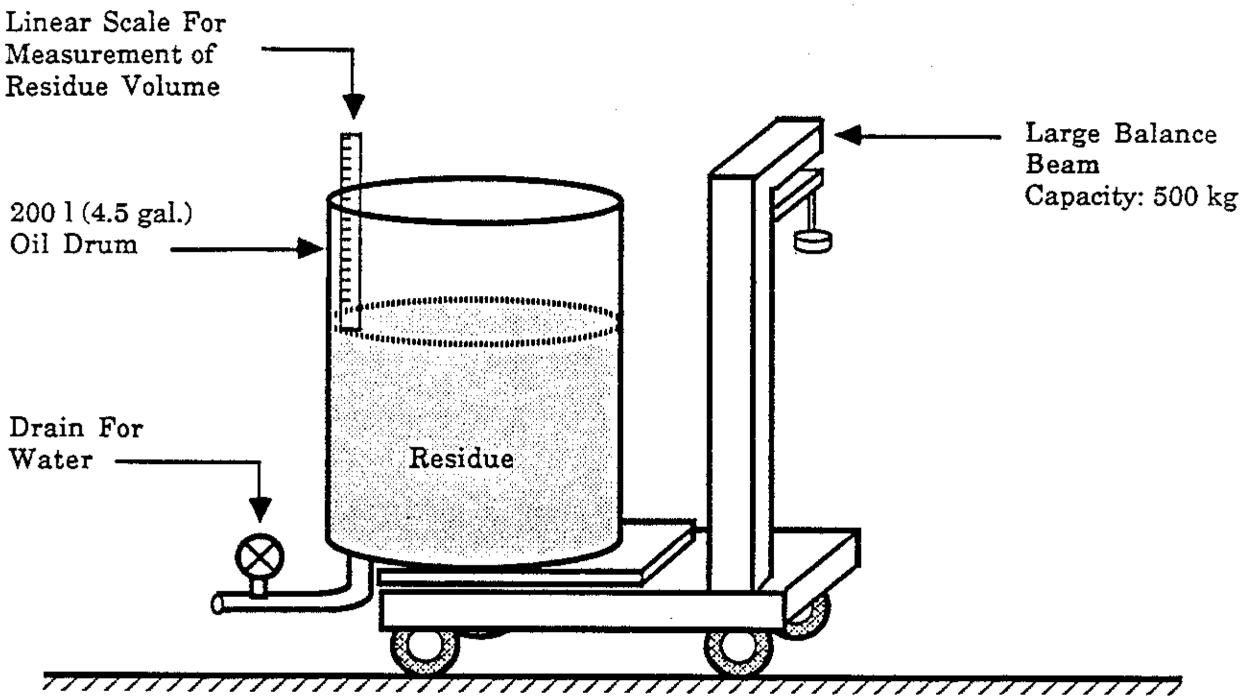


Figure 2.3 Schematic of Setup For Measurement of Weight and Volume of Residue

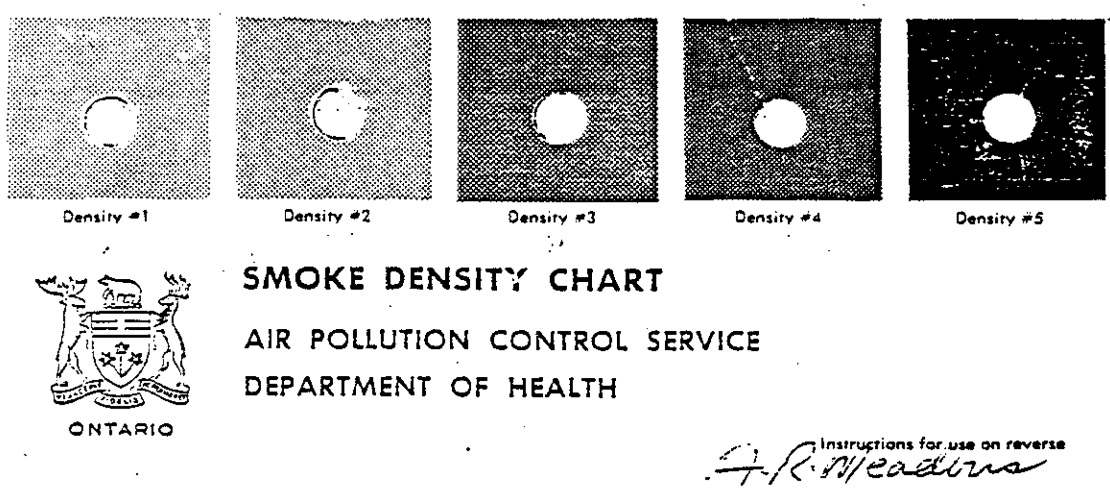


Figure 2.4 Smoke Density Chart

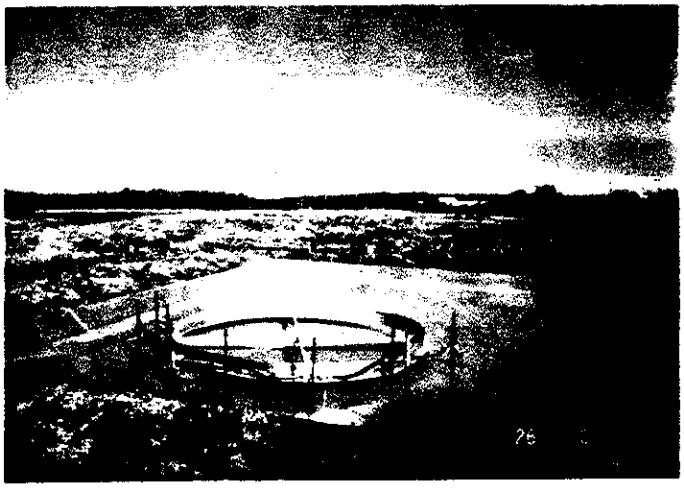
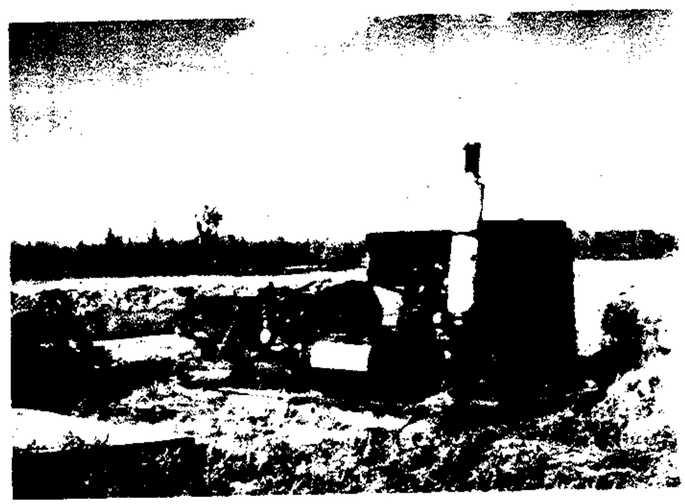


Plate 2.1

Test Basin

Plate 2.2

Pump and Prime Mover for High Pressure Waterjet Barrier



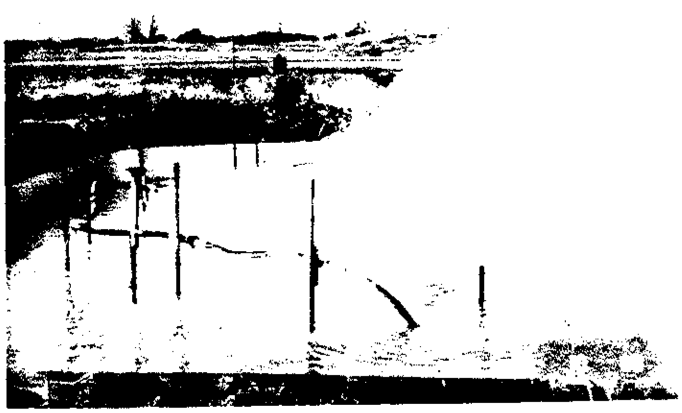


Plate 2.3

Waterjet Barrier in "V" Configuration

Plate 2.4

Waterjet Barrier in Circle Configuration

Plate 2.5

Oil Placed in Containment Ring

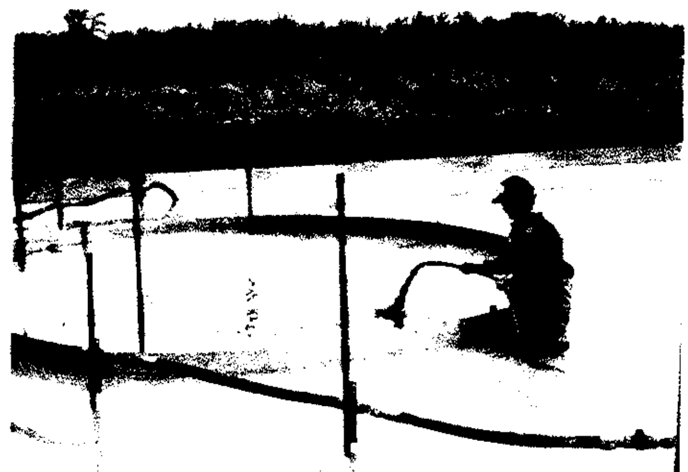


Plate 2.6

Ignition of Oil Slick

Table 2.1

Summary of Measurement Techniques

Test Parameter	Measurement Technique
Environmental Data:	
Air temperature	Mercury thermometer deployed at an elevation of about 1m.
Water temperature	Mercury thermometer deployed in upper 3cm of water column.
Ambient windspeed	Hand-held, direct-reading, propeller-type anemometer. A "turbo-meter" manufactured by Davis Instruments Ltd. was used. Windspeeds were measured approximately 3m above the water surface.
Wind direction	Noted qualitatively from direction of smoke plume.
Oil Burn Data:	
Weight of pre-burn oil and of residue	Oil, or residue, collected in drums and weighed using large balance beam scale.
Volume of pre-burn oil and of residue	Oil, or residue, collected in drums. Volume measured using linear scale.
Smoke plume density and reflectance	Reflectance measured using Pentax Spotmeter V and Pentax Gray Card of 18% reflectance. Smoke plume density inferred from measurements of the reflectance of the plume and of the Smoke Density Chart commonly used in conjunction with a Ringelmann Smoke Meter.
Duration of burn	Stopwatch.
Flame temperature	Spot measurement near the centre of the flame using a pyranometer supplied by Environment Canada.

Measurements were also made to determine the opacity of the smoke plume. The reflectance of the smoke plume was measured using a Pentax Spotmeter V and a Pentax Gray Card (of 18% reflectance). The luminance of both the plume and the card were measured for each test. Typically, the luminance of the smoke plume was measured near the centre of the plume. These data were used to determine the illuminance just before the test was commenced and the reflectance of the plume.

This was done by:

(a) determining the background illuminance just prior to the commencement of each test. To accomplish this, the exposure meter was aimed at the standard gray card (of 18% reflectance) and the exposure reading was noted. The illuminance was then computed using the manufacturer's calibration curve for the exposure meter.

(b) The reflectance of the plume was determined based on a knowledge of the background illuminance and on the measured exposure meter readings for the plume (which provided a measure of the luminance of the plume). These parameters are related as follows (Eastman Kodak Company, 1975):

Reflectance = Luminance/Illuminance

These data were also related to standard smoke densities shown by measuring the reflectance of the grey shades shown in Figure 2.4. These data are summarized in Table 2.2.

Table 2.2

Reflectance of Smoke Density Chart Shown in Figure 2.4

Date: November 17, 1988
Illuminance of Standard Photographic Gray Card of 18% Reflectance

Spotmeter Reading		
EV	Luminance (Foot-Lamberts)	Illuminance (Foot-Lamberts)
8.3	13	73

Reflectance of Smoke Density Chart

Density #	Spotmeter Reading EV	Luminance (Foot-Lamberts)	Reflectance
1	10.5	50	68%
2	9.9	40	55%
3	9.5	29	40%
4	8.7	18	24%
5	8.1	11	15%

2.1.3 Waterjet Barrier

As outlined in section 1.0, a large, prototype, high pressure waterjet barrier system has been developed and produced by Environment Canada. This prototype system was used in this project.

The setup of the waterjet barrier selected for these tests was based on the results of previous tests to optimize the performance of the system (Phillips et al, 1987) and on previous operating experience (e.g. Laperriere, 1985).

The table below describes some key setup parameters for the waterjet barrier:

Nozzle:	No. 6530 Spread angle: 65° Aperture: 0.13 in. Vertical angle between jet and water surface: 10°
Operating Pressure:	See following text.
Height of Nozzles:	15-30cm
Spacing of Nozzles:	2.5-3m
Configuration of Waterjet Barriers:	"V" and circle as shown in Figures 2.1 and 2.2.

Appendix A provides further information to describe the waterjet barrier system.

It was initially planned to operate the waterjet barrier at the same pressure used during previous laboratory tests (Phillips et al, 1987) and field deployment (e.g. Laperriere, 1985). The range of operating pressures tested in the laboratory by Phillips et al, 1987 was 6.9 to 20.7 mpa (1000 to 3000 psi). During a field deployment at Norman Wells, NWT, Laperriere, 1985 operated the waterjet barrier at 5.9 mpa (850 psi) and 9.0 mpa (1300 psi) in the deflection mode and at 9.7 mpa (1400 psi) in the collection mode.

During these tests, it was found that the operation of the waterjet barrier at pressures in excess of 6.9 mpa (1000 psi) caused a noticeable reduction in the extent of the flame which would have resulted in the eventual extinction of the flame. Furthermore, it was found that the oil became emulsified in the presence of the waterjet.

Consequently, it was decided to operate the waterjet barrier at lower pressure for these tests.

The maximum operating pressure for these tests ranged from 0.7 to 6.9mpa (100 to 1000 psi). These tests were conducted by instructing the technician operating the waterjet barrier to maximize the length of the burn. Efforts were made to operate the waterjet barrier at the pressure which provided maximum aeration of the flame. This was judged by the colour of the smoke and efforts were made to keep the smoke as clear as possible. When it was clear that the extent of the flame was being reduced by the jet, the pressure of the waterjet barrier was reduced and the flame was allowed to build. This sequence was repeated until the burn was complete and the flame was extinguished.

As will be discussed in section 3.0, the opacity of the smoke was significantly affected by the operation of the waterjet barrier. Special care was taken to operate the waterjet barrier so that the aeration of the flame was maximized, and hence the density of the plume was minimized. Thus, the results of this test program can be expected to overestimate the probable reduction in smoke density that would be achieved in a field deployment.

2.1.4 Oil Properties

Table 2.3 summarizes the available data to describe the properties of the oil used during the tests.

These properties were confirmed by Environment Canada who undertook analyses of oil samples collected during the test program.

2.1.5 Environmental Conditions

Efforts were made to conduct all of the tests in conditions of zero precipitation and low windspeeds.

Table 2.4 summarizes the environmental conditions for each test.

Table 2.3

Summary of Oil Properties
(Source: Gaiswinkler Enterprises Ltd., personal communication)

Oil Type:	Ontario Light Crude Oil	
Oil Properties:	Specific gravity at 60°F	: 0.816
	A.P.I. gravity at 60°F	: 41.9
	Sulphur percent (by wt)	: 0.18
	Pour point	: 15°F
	Colour	: greenish black
	Carbon residue percent (by wt)	: 1.0
	Saybolt universal viscosity at 100°F	: 39 sec.

Table 2.4

Summary of Environmental Conditions

Test #	Air Temp. (°C)	Water Temp. (°C)	Ambient Windspeed (m/s) Avg.	Ambient Windspeed (m/s) Peak	Precipitation
1	3.5	2.3	1.8	2.7	Nil
2	5.0	3.5	2.5	3.0	Nil
3	10.0	8.0	4.0	8.0	Nil
4	11.0	9.0	4.0	6.0	Nil
5	10.0	9.0	4.0	6.0	Nil
6	5.0	5.0	1.7	2.2	Nil
7	6.0	6.0	Nil	Nil	Nil
8	2.0	3.0	2.0	3.1	Nil
9	10.0	4.5	1.3	1.5	Nil
10	6.5	6.0	0.3	0.3	Nil
11	3.0	4.5	3.0	4.3	Nil
12	7.0	6.0	2.7	3.7	Nil

2.2 Test Conduct and Test Matrix

2.2.1 Test Conduct

Each test was conducted in the following sequence:

(a) Measure pre-test environmental data (i.e. air temperature, water temperature, windspeed) and the luminance of a standard photographic card (of 18% reflectance). Commence recording of the test using video photography.

(b) Place a known volume and weight of oil inside the containment ring. See plate 2.5.

(c) Ignite the oil using a torch. See plate 2.6.

(d) Commence the waterjet barrier within 30 seconds of ignition.

(e) Drop the containment ring to the bottom of the basin. (This was only done for the "uncontained" tests.)

(f) Measure the luminance of the smoke plume and the flame temperature. Photograph the test using 35mm cameras.

(g) Continue to observe the test until the fire was extinguished. record the duration of the burn. Efforts were not made to relight the oil slick once the flame was extinguished.

(h) Collect the residue and measure its weight and volume.

2.2.2 Test Matrix

The following parameters were systematically varied during the test program:

(a) the configuration of the waterjet barrier. Tests were carried out with the waterjet barrier deployed in a "V" and a circle as described in section 2.1. Also, some tests were carried out without the waterjet barrier.

(b) the thickness of the oil slick.

(c) the containment provided to the oil slick. The oil slick was either "contained" in a 5m diameter ring or "uncontained".

A total of 12 tests were carried out. The test matrix is summarized in Table 2.5.

Table 2.5

Test Matrix

Test #	Test Date	Mean Thick. of Oil Slick (mm)	Oil Slick Contained In Ring?	Waterjet Barrier Configuration		
				Not Operating	"V"	Circle
1	Nov. 4	9.9	Yes		✓	
2	Nov. 4	19.8	Yes		✓	
3	Nov. 6	19.8	Yes	✓		
4	Nov. 6	9.9	Yes	✓		
5	Nov. 6	9.9	No	✓		
6	Nov. 8	9.9	No		✓	
7	Nov. 8	19.8	No		✓	
8	Nov. 15	9.9	Yes			✓
9	Nov. 15	19.8	Yes			✓
10	Nov. 15	9.9	Yes			✓
11	Nov. 16	9.9	No			✓
12	Nov. 16	19.8	No			✓

3.0 TEST RESULTS

3.1 Qualitative Description of the Tests

3.1.1 Test Without the Waterjet Barrier

Tests 3, 4 and 5 were done with the waterjet barrier shut off. These tests were done to provide a baseline against which the effects of the waterjet barrier would be measured.

For tests 3 and 4, the oil was contained in the ring, and hence, the burn was confined to the ring.

Test 5 was an uncontained test. However, the oil was herded by wind action to the end of the tank before it could be ignited. The estimated size of the slick at the time of ignition was $40m^2$ and the mean oil slick thickness was computed to be 5mm. After the oil slick was ignited, the burn was confined to the area initially occupied by the slick.

Each of these burns was very rapid (with a burn duration of 5-6 minutes) and produced a large amount of black, dense smoke. See plates 3.1 to 3.3.

3.1.2 Tests With the Waterjet Barrier in the "V" Configuration

The oil was contained in the ring for tests 1 and 2, while the oil was uncontained for tests 6 and 7.

For the contained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated which pushed the burning oil slick towards the outer edge of the ring. The burning oil slick was estimated to cover about two thirds of the area inside the ring after the waterjets were activated. These burns were of long duration (i.e. 36 and 82 minutes) and the waterjets produced a noticeable reduction in smoke opacity. See plates 3.4 and 3.5.

For the uncontained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated and the containment ring was dropped to the bottom of the basin. For test 6, the burning oil was pushed to the end of the basin by the waterjets. See plate 3.6. The burn was confined to an estimated area of $40m^2$. The mean oil slick thickness over this area was computed to be 5mm.

For test 7, the containment ring was obstructed and did not drop cleanly to the bottom. This caused the oil slick to be more dispersed by the action of the waterjet (than was the case for test 6). However, soon after the ring was dropped, the oil slick was pushed towards the outer ring of the basin and was contained there for the remainder of the burn. See plate 3.7.

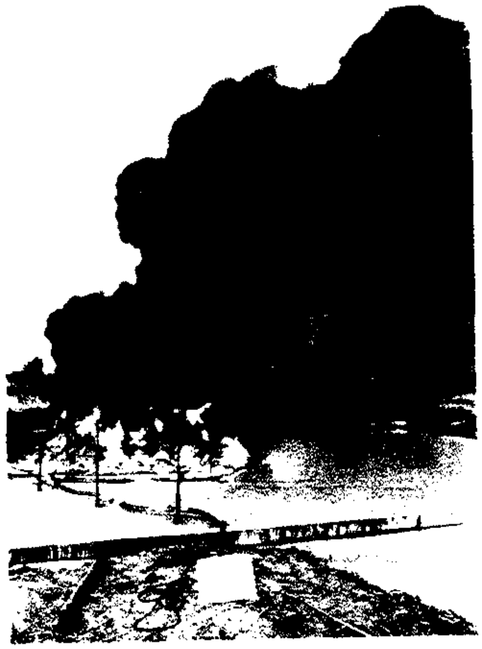


Plate 3.1

Test #3

Plate 3.2

Test #4

Plate 3.3

Test #5

Plate 3.4

Test #1

Plate 3.5

Test #2

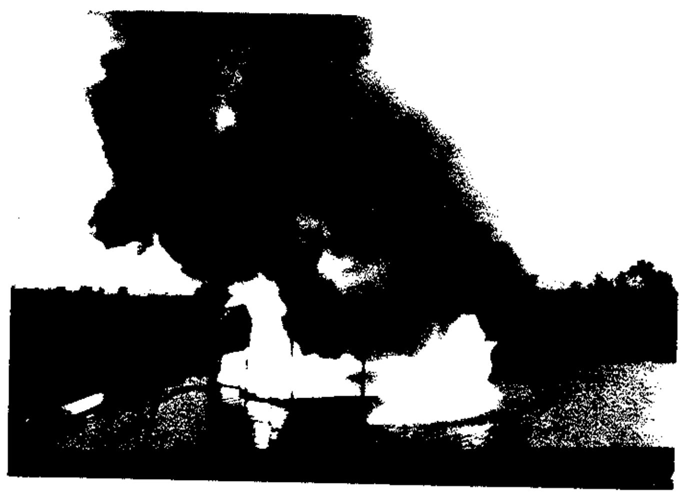


Plate 3.6

Test #6

Plate 3.7

Test #7

Plate 3.8

Test #8

Plate 3.9

Test #9

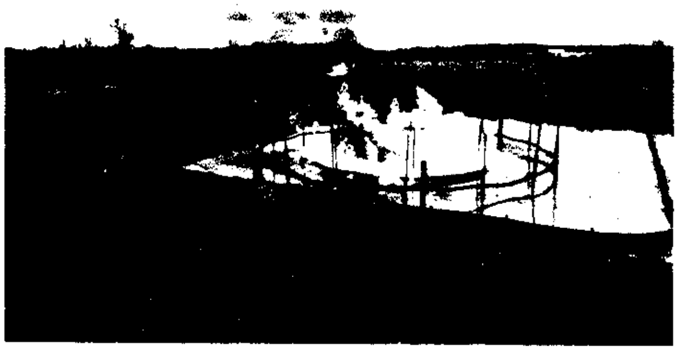


Plate 3.10

Test #10

Plate 3.11

Test #11

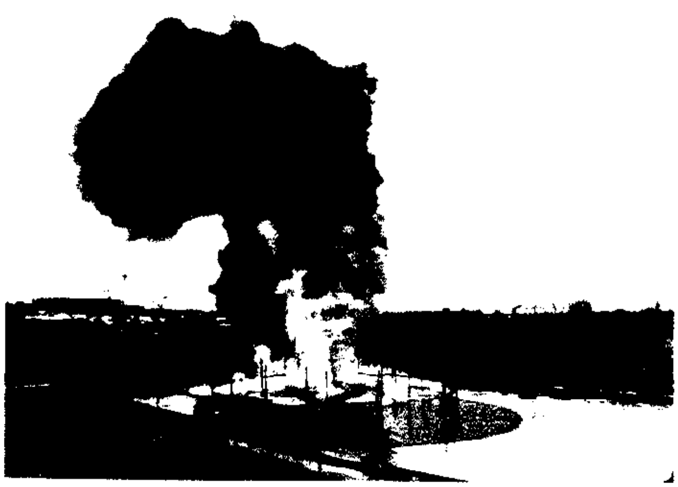


Plate 3.12

Test #12

The uncontained burns (i.e. tests 6 and 7) were very similar to the uncontained burn conducted with the waterjet barrier shut off (i.e. test 5). The duration of burns 6 and 7 was very short (i.e. 7 and 5 minutes respectively) in comparison to a burn duration of 5 minutes for test 5. Furthermore, burns 6 and 7 produced a large amount of dense, black smoke, which appeared similar to that produced by burn 5. In general, it appeared that the influence of the waterjets on the burn was minor and that the main effect of the waterjets during these uncontained tests was to herd the oil towards the end of the basin. The edge of the oil slick was relatively distant from the waterjets (i.e. about 10m) and little turbulence was produced by the waterjets on the water surface immediately in front of the slick perimeter.

3.1.3 Tests With the Waterjet Barrier in the Circle Configuration

The oil was contained in the ring for tests 8 to 10, while the oil was uncontained for tests 11 and 12.

For the contained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated which pushed most of the burning oil slick towards the centre of the ring into a circular slick about 3m in diameter. However, some oil remained near the outer edges of the ring as it was not contacted by the waterjets. Eventually, the oil near the edge of the ring was moved to the centre area by the surface currents induced by the waterjets. See plates 3.8 to 3.10.

The flame in the central portion of the ring was aerated by the waterjets and the smoke was light-coloured. The oil which had remained near the edges of the ring burned with a noticeably denser, black smoke.

Emulsions were formed during these tests. There was an especially large amount of residue from test 8 (i.e. 195% and 220% of the volume and weight of the spilled oil, respectively). Consequently, this test was repeated (as test 10). However, for test 10, the maximum operating pressure of the waterjet barrier was reduced to 0.7mpa (100 psi) from 2.1mpa (300 psi) for test 8. This was found to reduce the residue somewhat. For test 10, the weight and volume of the residue was 114% and 120% of that of the spilled oil, respectively.

The uncontained tests (i.e. tests 11 and 12) were conducted by placing the oil in the ring, igniting the oil, activating the waterjet barrier, and then dropping the containment ring to the bottom of the basin. For these tests, some of the oil escaped past the waterjet barrier when the containment ring was dropped. The oil which escaped was contained by the outer ring of the basin. Most of it was eventually moved back inside the circular waterjet barrier by the surface currents produced by the waterjet barrier where it was burned.

Thus, the burn was comprised of oil that was inside the waterjet barrier, which produced smoke that was light-coloured, and oil that was beyond the waterjets, which produced dense, black smoke. See plates 3.11 and 3.12.

3.2 Quantitative Test Results

Tables 3.1, 3.2 and 3.3 summarize the quantitative data that were measured during the test program.

3.2.1 Burn Efficiency

In general, the operation of the waterjet barrier was found to increase the weight and volume of the residue (in comparison to the tests done without the waterjet barrier). This is summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Residue As A Percentage of the Spilled Oil	
	Not Operating	"V"	Circle	By Volume	By Weight
Yes	✓			11-25	10-22
No	✓			9	9
Yes		✓		16-67	15-61
No		✓		27-42	24-39
Yes			✓	37-195	39-220
No			✓	22-53	24-57

The operation of the waterjet was observed to cause emulsification of the oil. This is believed to be one of the principal reasons for the increased amount of residue for the tests done with the waterjet barrier. Samples of the residue from tests 8-12 were were collected for subsequent analysis by Environment Canada. Table 3.4 summarizes the results of these analyses.

The moisture content of the residue from tests 8 to 12 was measured to range from 3% to 28% on a volume basis. These amounts are significantly less than would be predicted from the measured volume and weight of the residue.

A number of explanations for this discrepancy are possible, including:

(a) water was collected with the residue and not drained away prior to measuring the volume and weight of the residue. This is considered to be unlikely as care was taken to avoid the collection of water and to ensure that the water was drained prior to measuring the volume and weight of the residue.

(b) the sample of the residue which was retained for analysis was small and may not have been representative of the residue. (The volume of the sample was approximately 5cc, whereas the volume of the residue was of the order of 100 litres.)

Unfortunately, additional data are not available to resolve this issue.

For this report, we have elected to use the measured volumes and weights of the residue as a basis for discussing the test results as these data are available for each test.

The operating pressure of the waterjet barrier significantly affected the emulsification of the oil, and hence, the amount of residue. This is illustrated by the results of tests 8 and 10. These were duplicate tests with the exception that the maximum operating pressure of the waterjet was reduced from 2.1mpa (300 psi) for test 8 to 0.7mpa (100 psi) for test 10.

The weight and volume of the residue from test 8 was 195% and 220% of that of the spilled oil, respectively. For test 10, the weight and volume of the residue was reduced to 114 and 128% of that of the spilled oil, respectively. See Table 3.2.

The deployment of the waterjet barrier in a circle configuration was found to produce an increased amount of residue in comparison to the "V" configuration for the **contained** tests. See table above and Table 3.2. This is believed to reflect greater emulsification of the oil for the circle configuration.

For the **uncontained** tests, the amount of residue was generally similar for the "V" and the circle configurations. This is believed to reflect the fact that a significant volume of oil escaped past the waterjet barrier for the uncontained, circle configuration tests. (This occurred because the waterjet barrier was operated at low pressure to avoid extinguishing the flame and emulsifying the oil.) Thus, for both the "V" and the circle configuration, a significant proportion of oil was burned in areas removed from the influence of the waterjets.

These test results need to be interpreted with care as the oil slick was contained by the outer ring of the basin. It is expected that the oil slick would have dispersed further in a field deployment with the result that the burn efficiency would be lowered. This would cause these test results to overpredict the burn efficiency that would be achieved in a field deployment.

The amount of residue was also affected by the thickness of the oil. For each waterjet barrier configuration (i.e. not operating, "V", and circle) that was tested in the **contained** condition, the weight and volume of the residue was significantly less (by a factor of about 2) for the tests done with a slick thickness of 19.8mm, in comparison to those done with a slick thickness of 9.9mm.

3.2.2 Smoke Opacity

The operation of the waterjet barrier was found to generally reduce the density of the smoke plume, and to increase the reflectance of the smoke plume, in comparison to the tests done without the waterjet barrier. For those tests without the waterjet, the smoke plume was very dense throughout the duration of the burn. This is summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Reflectance of Smoke Plume (%)	Smoke Density Level**
	Not Operating	"V"	Circle		
Yes	✓			2-4	5
No	✓			4	5
Yes		✓		9-23	4-5
No		✓		5-17	4-5
Yes			✓	5-32	3-5
No			✓	2-54	2-5

**See section 2.1 and Figure 2.4 for a definition of the "smoke density level".

For the tests done in which the waterjet barrier was deployed in either a "V" or a circle configuration, the smoke plume was less dense. Furthermore, the density of the plume was more variable throughout the burn. This reflects the technique used to operate the waterjet barrier in which the pressure was varied to maximize the length of burn. The operation of the waterjet barrier was found to clearly reduce the opacity of the plume. However, when the extent of the flame was being reduced by the waterjets, and/or when the waterjets were considered likely to extinguish the flame, the pressure was reduced. This allowed the flame to grow and produced dense smoke. See section 2.1.3 for further description of the operation of the waterjet barrier.

Thus, it can be seen that special care was taken to operate the waterjet barrier to maximize the aeration of the flame. Thus, the results of this test program may overestimate the reduction in smoke opacity that would be achieved by the operation of the waterjet barrier in a field deployment.

The burns carried out in this test program were of relatively small scale. For a field deployment, the size of the slick is expected to be significantly greater than those tested in this program. This would cause the waterjet barrier to be farther away from the centre of the flame and may result in local aeration only at the perimeter of the flame by the waterjets. In this case, dense smoke is likely to be produced from the centre of the flame. Hence, the results of this test program are likely to overestimate the reduction in smoke opacity that would be achieved by the operation of the waterjet barrier in a field deployment.

Table 3.1

Summary of Oil Burn Data

Test #	Maximum Operating Pressure of Waterjet Barrier (mpa)	Burn Duration (min.)	Flame Temperature (°C)
1	6.9 (1000 psi)	36	1290
2	2.8 (400 psi)	82	1260 - 1510
3	Waterjet Barrier Off	6	1350
4	Waterjet Barrier Off	5	1550
5	Waterjet Barrier Off	5	1500
6	4.8 (700 psi)	7	1200
7	6.9 (1000 psi)	5	1400
8	2.1 (300 psi)	10	1400
9	0.7 (100 psi)	28	1590
10	0.7 (100 psi)	12	1500
11	2.1 (300 psi)	30	1400
12	2.1 (300 psi)	34	1400

Table 3.2

Summary of Oil Burning Efficiencies

Test #	Spilled Oil		Residue Remaining After Burn		Residue as a Percentage of the Spilled Oil	
	Vol. (l)	Wt. (kg)	Vol. (l)	Wt. (kg)	By Volume	By Weight
1	194	171	130	104	67	61
2	388	342	61	50	16	15
3	388	342	43	33	11	10
4	194	171	48	38	25	22
5	194	171	17	15	9	9
6	194	171	82[3]	66[3]	42[3]	39[3]
7	194	171	52[3]	41[3]	27[3]	24[3]
8	194	171	379[1]	376[1]	195[1]	220[1]
9	388	342	142	135	37	39
10	194	171	222[1]	219[1]	114[1]	128[1]
11	194	171	103[2]	97[2]	53[2]	57[2]
12	388	342	84[2]	83.5[2]	22[2]	24[2]

Notes:

1. Test 10 was a repetition of test 8. For test 10, the waterjet barrier was operated at a maximum of 100 psi (versus a maximum pressure of 300 psi for test 8).

2. These tests were uncontained with the waterjet barrier in a circle configuration. Oil escaped under the waterjet barrier and was contained by the outer ring. Some of the oil which escaped burned outside of the waterjet barrier. The remainder was moved back inside the waterjet barrier by the induced surface currents.

3. These tests were uncontained with the waterjet barrier in a "V" configuration. The oil was pushed by the waterjets to the end of the basin where it was contained by the outer ring. The estimated mean thickness of the oil slick at the start of the test was 5mm.

Table 3.3
Summary of Smoke Opacity Data

Test #	Luminance of Std. 18% Reflectance Gray Card		Illuminance (Foot-Lamberts)	Luminance of Smoke Plume		Reflectance of Smoke Plume (%)	Smoke Density[2]
	Spotmeter Rdg. (EV)	Luminance (Foot-Lamberts)		Spotmeter Rdg. (EV)	Luminance (Foot-Lamberts)		
1	10.2	46	256	10.5	60	23	4
2	9.0	21	117	8.0	10.5	9	5
3	12.3	210	1170	10.0	42	4	5
4	12.7	270	1500	9.5	30	2	5
5	14.0	670	3720	12.0	165	4	5
6	10.6	64	360	8.6	16.5	5	5
7	12.0	165	920	8.5	16	17	4-5
8	15.2	1450	8060	13.3	420	5	5
9	14.6	1000	5600	14.1-15.5[1]	700-1600	12-29	3-5
10	10.7	66	370	11.5	120	32	3-4
11	11.4	110	610	10-13[1]	41-330	7-54	2-5
12	13.5	460	2560	10.5-14.5[1]	60-900	2-35	3-5

Notes: 1. The smoke plume was alternately light and dark depending on the operation of the waterjet barrier.

2. See Figure 2.4 and Section 2.1.2 for definition of smoke density.

Table 3.4

Results of Oil Analyses Undertaken By Environment Canada

Oil Used for Test Program:

- Density: 0.8234 g/cc
- Viscosity at 60°F: 5.8 cps

Burn Residue:

Test #	Moisture Content (% by weight)	Maximum Variance (%)
8	23	7
9	28	5
10	14	2
11	18	6
12	3	1

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary

(i) Burn Efficiency:

(a) The operation of the waterjet barrier significantly increased the weight and volume of the residue (in comparison to tests done without the waterjet barrier). This is summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Residual As A Percentage of the Spilled Oil	
	Not Operating	"V"	Circle	By Volume	By Weight
Yes	✓			11-25	10-22
No	✓			9	9
Yes		✓		16-67	15-61
No		✓		27-42	24-39
Yes			✓	37-195	39-220
No			✓	22-53	24-57

The operation of the waterjet barrier was found to produce turbulence on the water surface and to cause the formation of emulsions. This is believed to be the principal reason for the observed reduction in burn efficiency.

(b) During the tests, care was taken to operate the waterjet barrier to minimize the formation of emulsions as follows:

- The waterjet barrier was operated at relatively low pressures (i.e. a maximum of 0.7 to 6.9mpa over the duration of the tests). These pressures are significantly less than the pressure (of about 14mpa) that previous laboratory tests had shown to provide maximum oil slick retention capability without emulsifying the oil.
- For the tests in which the waterjet barrier was deployed in a circle and the oil slick was contained, the waterjets were set up to avoid direct impingement on the oil. The waterjets were positioned such that they just cleared the top of the containment ring.

On the other hand, the tests were done on a relatively small scale. For a large burn in the field, the formation of emulsions (produced by the action of the waterjet barrier) is expected to be localized at the perimeter with the result that higher burn efficiencies may be achieved.

Thus, the results of this test program may underestimate the burn efficiencies that would be achieved in a field deployment.

(c) The burn efficiency increases significantly with the slick thickness. For the tests done with a mean slick thickness of 19.8mm, the weight and volume of the residue (expressed as a percentage of that of the spilled oil) was about one quarter of that left from the burns done with a mean slick thickness of 9.9mm.

(d) The weight and volume of the residue was increased when the waterjet barrier was deployed in a circle for the contained tests (in comparison to the "V" configuration). This is believed to reflect increased emulsification of the oil for the circle configuration.

(e) For the uncontained tests, the circle and "V" configurations produced residues that approximately equal in weight and volume. This is believed to reflect the fact that some of the oil escaped past the waterjet barrier in the circle configuration.

(f) The uncontained tests were not free from edge effects as the oil was contained by the outer ring of the basin. It is expected that the oil slick would have been more dispersed in a field deployment and that the burn efficiency would be lowered. This would cause these test results to overpredict the burn efficiency that would be achieved in a field deployment.

(ii) Smoke Opacity:

(a) The operation of the waterjet barrier was found to reduce the opacity of the smoke, as summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Reflectance of Smoke Plume (%)	Smoke Density Level**
	Not Operating	"V"	Circle		
Yes	✓			2-4	5
No	✓			4	5
Yes		✓		9-23	4-5
No		✓		5-17	4-5
Yes			✓	5-32	3-5
No			✓	2-54	2-5

**See section 2.1 and Figure 2.4 for a definition of the "smoke density level".

(b) The results of this test program are expected to overestimate the probable reduction in smoke opacity that could be achieved by the use of the waterjet barrier in a field deployment as:

- special care was taken to operate the waterjet barrier to maximize the length of burn.

- the tests were done on a relatively small scale which allowed the waterjet barrier to provide relatively good aeration over the whole flame area.

4.2 Conclusions

The test program has provided data and observations for a preliminary assessment of the effect of a waterjet barrier on the burn efficiency of a floating oil slick.

The following conclusions are drawn from this test program:

(a) the operation of the waterjet barrier increased the volume and weight of the residue (in comparison to the tests done without the waterjet barrier) as it caused the formation of emulsions.

(b) the operation of the waterjet barrier reduced the opacity of the smoke.

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APPENDIX A

Waterjet Barrier Description

EXCERPT FROM PHILLIPS ET AL, 1987

LABORATORY TESTING TO OPTIMIZE THE PERFORMANCE OF A HIGH PRESSURE WATERJET BARRIER

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ABSTRACT

The premise that an oil spill may be contained by means of a high pressure waterjet barrier has spurred research efforts towards developing an effective prototype. In this paper, laboratory tests are reported which investigate the influence of various parameters on the performance of the waterjet barrier. An existing waterjet system was set up in Arctec Canada's environmental test basin in Kanata, Ontario. During the tests, measurements of the mean velocity of the two-phase airflow were obtained using a laser doppler anemometer. The matrix of parametric variations included: manifold pressure, nozzle spacing, height above the water free surface, depression angle, and nozzle characteristics.
From the analysis of these results it has been possible to identify an optimal nozzle type and the most efficient spacing of the jets.

TABLE 2

NOZZLE CHARACTERISTICS

TYPES	NOZZLE SPREAD ANGLE	NOZZLE APERTURE	MAXIMUM FLOW RATE (GPM) AT PRESSURE (psi)				
	(deg)	(inch)	1000	1800	2000	2500	3000
2510	25						
4010	40	0.075	5.0	6.1	7.1	7.9	8.7
6510	65						
2520	25						
4020	40	0.106	10.0	12.3	14.1	15.8	19.3
6520	65						
4030	40	0.130	15.0	18.4	21.0	24.0	26.0
6530	65						
2540	25						
4040	40	0.150	20.0	24.0	28.0	32.0	35.0
4060	40	0.183	30.0	37.0	42.0	47.0	52.0

CONCLUSIONS

The problem of optimizing the operation of the high pressure waterjet barrier has been examined in this report. An experimental investigation was carried out in which the airflow velocities were measured and their variation with relevant parameters was identified. Based on the present experimental results the following conclusions may be drawn:

1. The laser doppler anemometer system proved very successful as a means of measuring the airflow velocities induced by the high pressure waterjets.
2. It was found that normal shape curves provided a good fit to the velocity cross-section data. Exponential decay curves described the longitudinal velocity profiles along the waterjet centreline. The use of normal curves allowed a convenient representation of the effectiveness of different nozzle types in terms of the velocity flux and its corresponding broadness.
3. A methodology of establishing optimum spacing of multiple waterjets was proposed which utilized the collected broadness data from the single nozzle tests. The required spacing was 2.3 times the broadness of the cross-sectional velocity profile at a given distance from the waterjet.
4. An estimation of minimum power requirements was provided for each of the nozzles tested. The trends observed in the airflow analysis and power calculation suggested that selection of a small aperture, large flare angle waterjet nozzle will result in optimum performance of the barrier.

Several trends in operational parameters were identified during the course of the study:

5. ° Optimum nozzle height was observed to be between 15 cm and 30 cm above the spill. The relative insensitivity of the airflow to changes over this range suggests that greater jet heights may be practical for containment in wave environments.
   ° Small depression angles cause a rapid deterioration in the airflow; hence in practical operation of the waterjet barrier the stability of the floats will play a significant role.
   ° Increasing pressure between 6900 kPa and 20,680 kPa appeared to cause an increase in airflow velocities, although some discrepancies were observed in this data. However, the penalty in horsepower associated with increased pressure, as well as increased hosing costs would argue against pressures in excess of 10,200 kPa (1500 psi).

TABLE 3

SUMMARY OF MULTIPLE NOZZLE OPTIMUM SPACINGS

NOZZLE TYPE	TEST NO.	PRESSURE (kPa)	OPTIMUM SPACING AT 3.05 m (m)	MEAN AIRFLOW VELOCITY m/s at 3.05 m	OPTIMUM SPACING AT 10 m (m)	MEAN AIRFLOW VELOCITY m/s at 6.10 m
2510	5	13790	1.022	17.1	2.027	9.3
4010	3	13790	1.494	14.0	2.448	7.8
2520	2	13790	.973	21.5	2.323	12.8
4020	1	13790	1.942	17.2	3.577	8.9
6520	4	13790	3.868	7.9	-	-
6530	7	13790	2.852	14.0	5.690	8.8
2540	6	13790	1.024	32.3	2.056	18.9
4040	8	13790	1.442	23.3	3.084	13.9
4060	9	13790	1.061	62.6	2.565	17.5

TABLE 4

POWER REQUIREMENTS

NOZZLE TYPE	Q_{max} gpm	HHP_{max} per nozzle	SPACING, m (at 6.1 m)	HHP_{max} per meter length
2510	7.1	8.28	2.027	4.08
4010	7.1	8.28	2.448	3.38
6510	7.1	8.28	-	-
2520	14.7	16.45	2.323	7.08
4020	14.7	16.45	3.577	4.60
6520	14.7	16.45	-	-
6530	21.0	24.50	5.690	4.31
2540	28.0	32.67	2.056	15.89
4040	28.0	32.67	3.084	10.59
4060	42.0	49.01	2.565	19.11

HIGH PRESSURE WATERJET BARRIER TRIAL IN NORMAN WELLS

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Introduction

The high pressure waterjet concept for controlling oil on the surface of the water was found promising for Arctic use in broken ice where usual response techniques are not effective. It was first evaluated at OHMSETT (Meikle, 1983) with a small scale simulation of a barrier consisting of 3 jets. It was tested under calm conditions and in current and waves, with a 2 mm Circo oil slick. The different parameters studied were pressure, flow rate, jet height above the oil surface and flare angle, current and waves. The high pressure waterjet concept was found efficient in calm water as well as in choppy waves. Optimum values from the tests were used to build a 30.5 m (100 ft.) long prototype in order to evaluate the operational efficiency of such a barrier. The system built was functionally tested near Vancouver, in calm water and without oil prior to being sent to Norman Wells, NWT.

Objectives

The objective of the trial at Norman Wells was to assess the operational effectiveness of the prototype with Canola oil in a current in the containment and deflection configuration.

Testing Location

The testing was executed on the MacKenzie River in August, 1984 with the participation of Esso Resources Canada Limited. The test area was near a small bay providing access to high and low current areas.

Barrier System

The barrier system includes; a power unit, a pressure/flow control panel, a supply line from the control panel to the barrier, two arrays of 5 interconnected spray nozzle assemblies.

The power unit consists of 3 components mounted on a steel skid of 4.2 m long x 2.1 m wide (14 x 7 ft) which weighs altogether about 6 600 kg (14 500 lbs). The components are (Figure 1):

- A GM Detroit diesel engine (model 8V 92T) delivering 550 BHP at 2 100 RPM with 115 mm (4.5 in) injectors.
- A horizontal OPI triplex plunger pump (model 500 AWS) with 88.9 mm (3.5 in) diameter plungers delivering 144 L/min. at 71 791 kPa to 1 136 L/min at 16 748 kPa (38 US gpm at 10 412 psi to 337 US gpm at 2 100 psi) from 50 RPM to 450 RPM (reduction gear ratio 4.68:1) with 271 BHP to 500 BHP required. The pump, having two 76 mm (3 in) high pressure ports, is equipped with an airflow discharge pipe. Its dimensions are 170 cm long (62 in), 136 cm wide (54 in), 80 cm high (32 in).

- A Mission supercharging centrifugal pump with a 112 mm (4 in) suction diameter and a 76 mm (3 in) discharge diameter delivering a maximum of 2 271 L/min. (600 US gpm) at 2 000 RPM, and a maximum pressure of 150 kPa (22 psi). The power required is 10 BHP. Its suction head is 2.4 m (8 ft.).

The barrier is composed of 10 sets of 2 opposed spray nozzles (316 stainless steel Vee Jet 6520, 2.78 mm (7.8 in) orifice diameter, horizontally oriented, 65° flare angle) mounted back to back, directed towards the inlet end at 60° to the line of the barrier. These nozzles are approximately 10 mm (4 in) above the water surface. The spray assemblies are interconnected with flexible high pressure hoses (3.8 cm ID (1.5 in.), 34 475 kPa (5 000 psi)) at a 2.4 m (8 ft) spacing (Figure 2). All the fittings and connectors are made of schedule 40 steel.

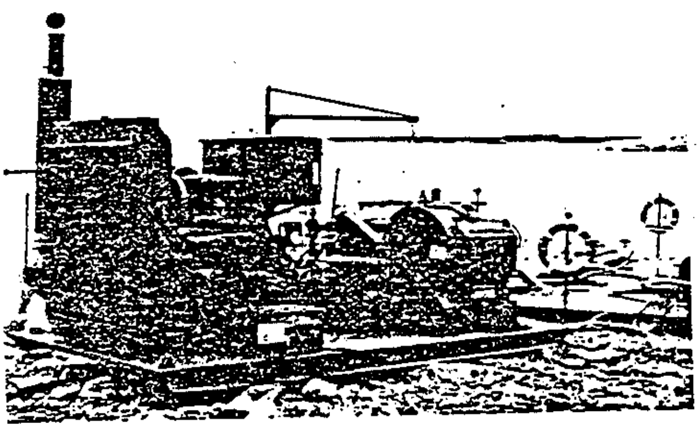

FIGURE 1

THE POWER UNIT

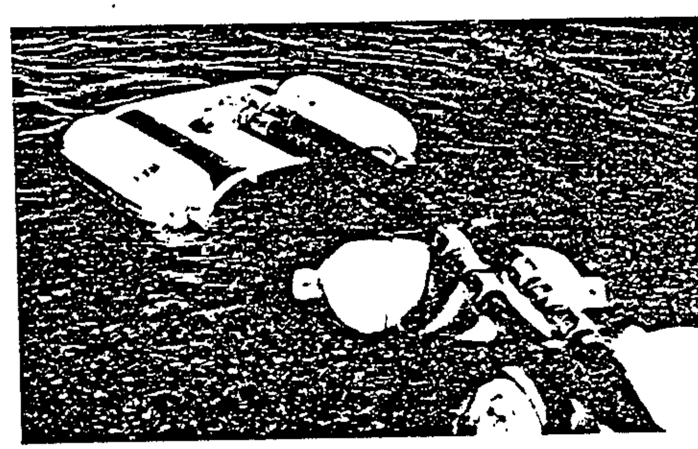

FIGURE 2

A WATERJET BARRIER SECTION

In the containment configuration 2 arms consisting of 5 spray nozzle each are attached to a 4-line hose bundle connecting them to the control panel 15.3 m (50 ft) away. In the deflection mode the two arrays of spray nozzle assemblies are connected in series and one end is attached to the supply bundle.

The pressure/flow control panel consists of a reverse U-shaped pipe on which four independent overloading valves interconnect two flexible high pressure hoses 9 m long (30 ft), 5 cm^{ID} (2 in), 34 475 kPa (5 000 psi)) coming from the high pressure pump ports to four 15.3 m (50 ft) long flexible distribution lines (3.8 cm^{ID}, (1.5 in) 34 475 kPa (5 000 psi)) going to the barrier (two of them are used for the deflection configuration and all four are used for the containment configuration). Manifolds and pressure gauges permit the operator to control the barrier. The panel has to be mounted at a location providing the operator a good view of all the area in which the barrier will operate.

Flotation platforms using two vinyl boat floats support the pairs of spray nozzles. A pair of vinyl boat floats support the two interconnecting hoses. The hoses are crossed over each other to overcome torque due to high pressure. Flexible couplings at each end of the hose segments also contribute to the stability of the system.

The volume of these 10 platforms with the hoses and the single float is approximately 3.0 m^3 (100 ft^3) and their total weight 1 590 kg (3 500 lbs).

Assembly and Deployment

The power unit was transported to the test location on a flatbed truck and put in place using 2 forklifts. Levelling was accomplished using the forklifts. The control panel was fixed on a barge facing the test location and near the pump. The installation of the manifold system with the pump high pressure discharging hoses, the distribution hoses and the low pressure intake hose (10.2 cm ID (4 in), 690 kPa (100 psi)) took 30 minutes using 3 people.

The barrier was first assessed in the deflection mode. The assembly of the 10 segments with the interconnecting hoses to the tube bundle took 1 hr using 3 people. Precautions were taken to prevent rocks from getting into hoses but some nozzles had to be unplugged during the first test. The end nozzle on the forward side had to be inclined to compensate for the inevitable inclination of the last flotation platform.

Most of the attachments of the hose floats had to be secured and/or replaced because of damage during shipment. A more durable design for these attachments is needed. Floaters were also attached to the distribution lines to reduce the drag.

Problems in priming the feed pump occurred. A trash pump in the feed line was first used but subsequently the feed line was manually filled. It was noticed that the pump base bearings were loosening rapidly due to vibrations.

Two pressure ranges were assessed using the barrier in the deflection mode. The wind velocity and direction during this part of the testing was 6 - 8 kn NE. At 5 861 kPa (850 psi), 348 L/min (92 US gpm) were necessary to move the barrier from at rest in the low current area of the bay toward the river using the aft nozzles. Using 696 L/min (184 US gpm) and the same pressure, angles of up to 30° with a 1.7 kn current could be reached and easily maintained (Figure 3, position 1). An anchor placed at the end of the barrier facilitated reaching a 30° angle. Small waves generated by a boat did not affect the alignment of the barrier maintained at 20° to the current direction. At angles higher than 30°, with the same pressure and flow, all the power was used by the nozzles on the aft side to hold position against the current. Oil deflection would not be possible at angles higher than 30° at 5 861 kPa (850 psi). The limiting pressure to maintain a

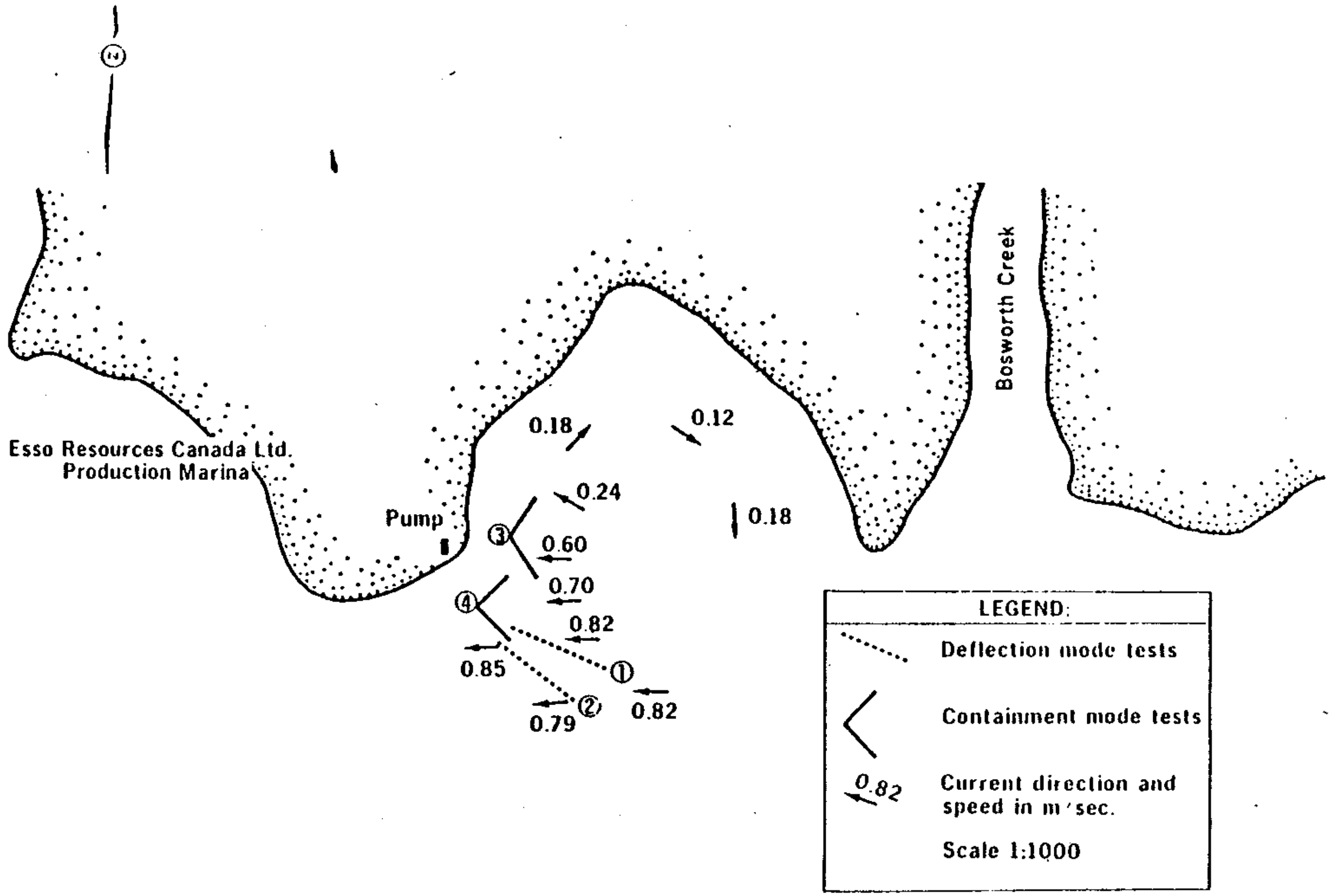

FIGURE 3 NORMAN WELLS TEST SITE

deflection at the same location was found to be 3 448 kPa (500 psi) with 538 L/min (142 US gpm).

The other pressure tried was 8 964 kPa (1 300 psi) with 863 L/min (228 US gpm). These settings permitted the deflection barrier to maintain an alignment of 40° with the current without bending (Figure 3, position 2). The limiting conditions for this deflection were 8 274 kPa (1 200 psi), 825 L/min (218 US gpm). Using the required settings for a 40° deflection barrier configuration a test was carried out with peat moss and vegetable oil, Canola oil not being available at that time (Figures 4, 5). The peat moss released approximately 5 m (17 ft) from the barrier never came closer than 1 m (3 ft) from the nozzles, going down current.

The collection configuration was tested in the bay as well as in the river (Figure 6). The conversion time to this configuration from the deflection configuration was 15 minutes using 3 people. Two operators were now required to handle the four manifolds controlling the pressure in the four distribution lines. The control unit was moved from the barge to the shore, the barge being needed. The operators, being now at the same level as the watersprays with the wind blowing towards them at 5 kn were blinded by waterjets. In the bay (Figure 3, position 3) at 9 653 kPa (1 400 psi) 910 L/min (238 US gpm) the two arms could be manoeuvered from 180° to 0° (inside angle) easily. A 120° opening configuration was tested with peat moss and vegetable oil. The peat moss was released 8 m away from the ends of the barrier in front of its center and stayed in the middle of the barrier no closer than 1 m to the arms.

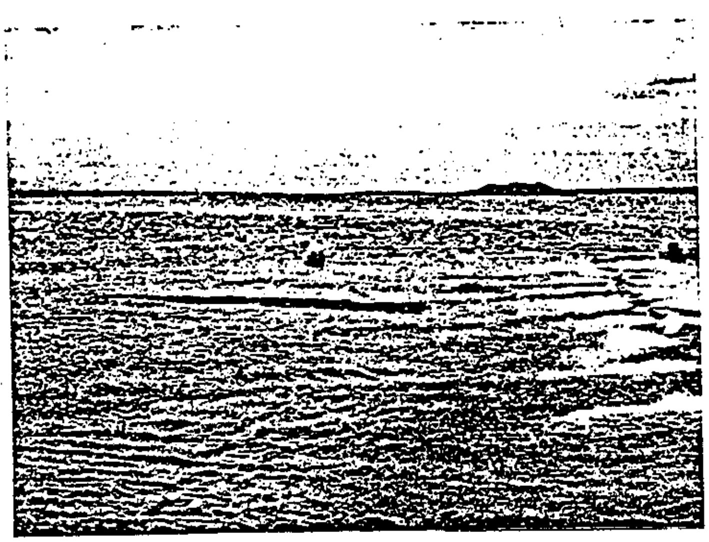

FIGURE 4

RELEASE OF PEAT MOSS AND VEGETABLE OIL IN FRONT OF THE DEFLECTOR

FIGURE 5

LOSS OF PEATMOSS AT THE END OF THE DEFLECTOR

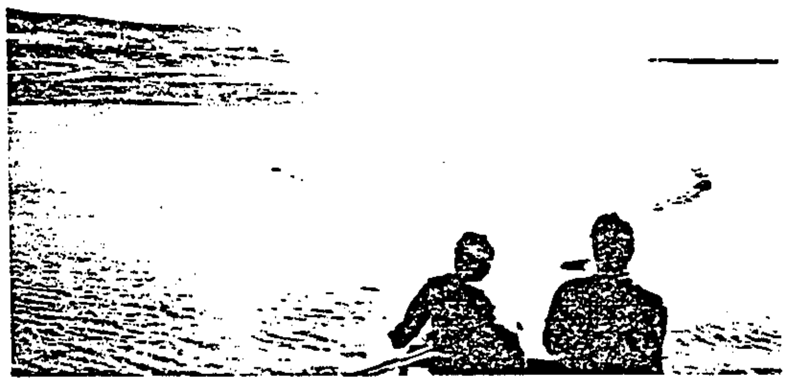

FIGURE 6

BARRIER IN A CONTAINMENT MODE

In the river, at the same operating conditions as in the bay, the two arms could be opened up to 90° (inside angle) at the most in order to contain oil (Figure 3, position 4). At higher openings the arm in the high current area could not withstand the current while providing containment sprays. Unfortunately, this 90° could not be tested with vegetable oil and peatmoss because all the materials were used in earlier tests.

As an oil deflector in the river the waterjet barrier operating at 5 861 kPa (850 psi), 696 L/min (184 US gpm) surpassed the deflection capability of conventional booms which is 20° in 1-2 kn current.

As an oil collection system in a 2 kn river current the waterjet barrier, operated at 9 653 kPa (1 400 psi), 901 L/min (238 US gpm) with a 90° opening, is expected to effectively contain an oil spill.

Re-design of the flotation platforms and of the control panel are planned in order to reduce drag and improve the manoeuverability of the barrier in current. Testing in the Frazer estuary and delta is scheduled for the summer and fall of 1985.

Reference

Meikle, K.M., "The Use of High Pressure Water for Spill Containment", Proceeding of the Sixth Arctic Marine Oilspill Program Technical Seminar, June 14-16, 1983, Edmonton, Alberta, p. 119-125.